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Factors Affecting the Visual Fragmentation of the Field-of-View in Partial Binocular Overlap Displays

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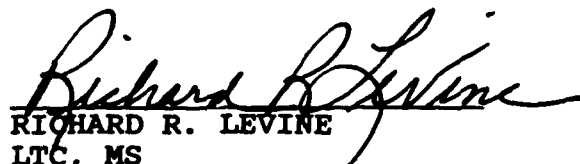Destroy this document when it is no longer needed. Do not return it to the originator.

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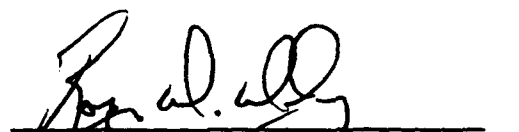
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Luning is a detrimental visual effect characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. With sufficiently small visual fields, luning is experienced as fragmentation of the field-of-view (FOV) into three regions, with the binocular overlap region appearing to be distinct and phenomenally segregated from the monocular side regions. Visual fragmentation of the FOV is likely the result of the binocular rivalry and suppression caused by the dichoptic competition between the images in the two eyes. The effect of the following factors on fragmentation was investigated: (1) the display mode--convergent versus divergent; (2) the size of the monocular regions; (3) the size of the monocular fields; (4) the size of the FOV; and (5) the size of the binocular overlap region. Thirteen Army aviators served as subjects in a design, where each subject made forced-choice fragmentation judgements of 25 different pairs of stimuli in which these five factors were varied systematically. The results showed that the divergent display mode systematically induced more fragmentation than the convergent display mode and also that patterns with a smaller binocular overlap
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region tended to fragment more than patterns with a larger binocular overlap region. The remaining three factors had no influence on fragmentation. In addition, neither optical convergence nor the retinal location of the blind spot were shown to be important factors. Ecological interpretations of our results are discussed. When a partial binocular overlap display is needed to increase the FOV to aviators in helmet-mounted displays, the convergent display mode with the larger binocular overlap region appears to be the best of the conditions tested to attenuate the fragmentation effect of luning. Additional factors are discussed.

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Introduction

Small fields-of-view (FOV) are detrimental to the visual tasks required of military pilots (Osgood and Wells, 1991; Wells, Venturino, and Osgood, 1989). In order to increase the extent of the visual world available to U.S. Army helicopter pilots using helmet mounted displays (HMD), without incurring increases in size or weight or losses in central resolution, an unusual method of display — partial binocular overlap — has been proposed. Two flanking monocular regions and a central binocular overlap region constitute the FOV in partial binocular overlap displays. Increasing the FOV by this method has been the cause of some concern (see Alam et al., 1992; Edgar et al., 1991; Kruk and Longridge, 1984; Landau, 1990; Moffitt, 1989; see Moffitt, 1991 and Moffitt and Melzer, 1991, for a tutorial description). One detrimental consequence of the partial binocular overlap display mode is a perceptual effect known as luning, which is a subjective darkening in the monocular regions of the FOV (Moffitt, 1989). When the display size is sufficiently small, luning is experienced as a visual fragmentation of the FOV into three distinct regions. The purpose of our study was to investigate the relative influence of a number of visual factors on the fragmentation of partial binocular overlap displays. First, we define a few concepts to avoid the ambiguity of the literatures on vision and display systems (see Farrell and Booth, 1984).

Background concepts

In the visual displays described here, background is the black region surrounding the visual fields, which are the intentionally stimulated visual areas seen by each eye. Access to the visual world is assumed to occur only through these artificial visual fields. Field-of-view (FOV) refers to the total extent of the visual world that is seen in a binocular HMD when both eyes are open. It includes what is seen by both eyes together as well as by each eye alone. The portion of the visual world that one eye sees is referred to as its monocular field. The portion of the visual world that both eyes see together is referred to as the binocular overlap region, and the portion of the FOV that only one eye sees is a monocular region. Thus, the FOV may consist of a binocular overlap region and a monocular region for each eye (see Figure 1).

As noted previously, a monocular field consists of two areas, a monocular region seen exclusively by one eye, and the area which is seen by both. Separating these two areas of the monocular field is the binocular overlap border. The term *dichoptic* refers to a situation where there is a simultaneous but dissimilar stimulation to the two eyes; thus, a monocular region and its corresponding region in the other eye, as well as the binocular border, are dichoptic (see Figure 1). The binocular attainment of singleness of vision (and stereopsis) results from the binocular fusion of monocular stimuli in corresponding retinal regions of each eye. Diplopia, or double vision, results when corresponding monocular stimuli fail to be fused.

When the two eyes are presented with exactly the same portion of the visual world, the viewing situation is referred to as the full binocular overlap display mode. In this case, the FOV consists solely of a binocular overlap region, in which the two monocular fields are coincident

and there are no monocular regions. The partial binocular overlap display mode occurs when each of the two eyes sees a portion of the visual world in common — the binocular overlap region — and, in addition, each eye sees an exclusive portion of the visual world in the monocular region (see Figure 1).

A word of caution on the difference in the use of terms in the applied display literature compared to the basic vision literature is that the display literature often refers to the effective or intended visual experience rather than the normal or potential experience. For example, the terms "field-of-view" and "monocular fields" refer to the intentionally induced, or effective FOV and monocular fields. This usage may have the unintentional effect of ignoring factors outside the display definitions, such as the low luminance background surrounding the effective FOV. With this in mind, unless indicated we follow the display literature terms defined here.

Partial binocular overlap displays contain binocular overlap borders, which in terms of the FOV separate the binocular overlap region and the monocular regions. In terms of the monocular fields, these borders separate the portion exclusively seen by one eye from the portion seen in common with the other eye. In normal unencumbered vision, the binocular overlap borders dividing the natural FOV are not experienced per se (see Gibson, 1979, for a good discussion) and are only cognitively identified and located with attentional effort. However, in artificial viewing situations such as HMDs where the monocular fields are smaller than in natural viewing, these borders are accompanied by a perceptual effect that in the display literature has come to be known as *luning* (Moffitt, 1989).

Fragmentation and luning

Luning is a visual perception characterized by a subjective darkening of the visual field in the monocular regions of partial binocular overlap displays. Having been first documented with binocular helmet mounted displays used in simulators (CAE Electronics, 1984), luning was so named because of the crescent shapes of the darkened monocular regions adjacent to the circular binocular overlap region (Moffitt, 1989; Melzer and Moffitt, 1989). It is most pronounced near the binocular overlap border separating the monocular and binocular regions, gradually fading with increasing distance from the border (see Figure 1). The magnitude of luning can fluctuate over time in terms of the size of the darkened region and the relative darkening. Luning appears not to be strongly under attentional control. With sufficiently small visual fields, luning is experienced as fragmentation of the FOV into three phenomenally distinct regions, where instead of the entire FOV appearing as one unitary visual area, the central binocular overlap region appears to be different than the two monocular side regions. The monocular regions may appear to lie in a different depth plane, or to be darker than the binocular region. The monocular regions may appear less substantial and less stable than the binocular overlap region in that they may fluctuate in appearance over time.

Fragmentation and luning are likely due to binocular rivalry and suppression. *Binocular rivalry* refers to the phenomenal (i.e., the subjective) alterations in appearance of a binocular

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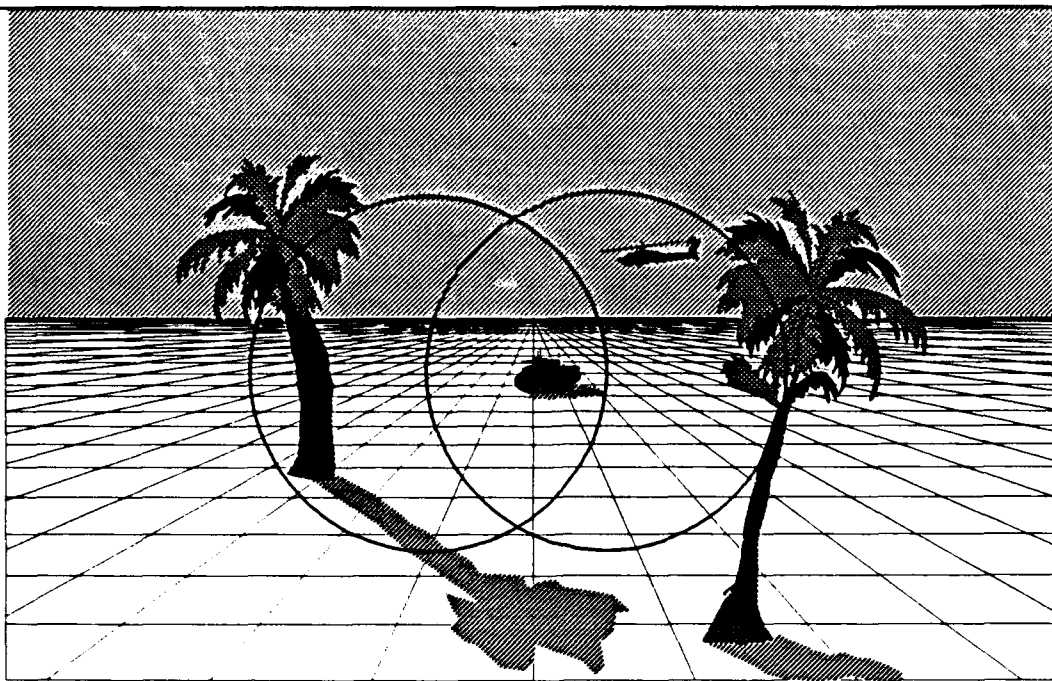
Figure 1. *A helicopter pilot's view of the visual world using a helmet mounted display in the partial binocular overlap display mode, where each eye sees a circular monocular field against a black background. The armored personnel carrier is in the binocular overlap region. Flanking this region are the two monocular regions. A helicopter is in a monocular region. If the right eye views the circular field on the right, the effective field-of-view is in the divergent display mode; if the right eye instead views the left circular field, the mode is convergent. Separating the central binocular region and flanking monocular regions are the binocular overlap borders. Under some conditions, these borders become phenomenally apparent, where the field-of-view no longer appears to be a unitary and continuously clear view of the visual world.*

Luning refers to the subjective darkening which can occur in the flanking monocular regions near the binocular overlap borders. Fragmentation is the appearance of the field-of-view as three phenomenally distinct regions. These deleterious effects are caused by strong dichoptic stimulation from the dark background and monocular field borders in each eye with the corresponding locations within the monocular field of the contralateral eye.

The purpose of the current study was to investigate how fragmentation is influenced by the display mode, and by the sizes of the monocular regions, the monocular fields, the field-of-view, and the binocular overlap region.

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stimulus, which is dichoptic, in our case the monocular regions in the partial binocular overlap display mode. Over time, one and then the alternative dichoptic stimulus may successfully compete and dominate awareness. *Suppression* refers to the phenomenal disappearance of one eye's input due to monocular dominance by the other eye. *Partial suppression* refers to the partial disappearance of one eye's input. In the partial binocular overlap display mode, each eye's monocular region is the result of dichoptic competition between a portion of its monocular field and the dark background and monocular field border of the other eye. If the background is completely suppressed, the FOV looks natural, and the binocular and monocular regions are both seen as one continuous visual world. If one eye's monocular region is partially suppressed by the dark background of the other eye, then this dark background will appear in the monocular region of the first eye with the greatest darkening — luning — occurring near the binocular overlap border. With a sufficiently small display size, this luning is experienced as a fragmentation of the FOV into three distinct visual regions where the two flanking monocular regions appear separate from and different than the central binocular overlap region. We refer to the eye contributing the monocular field to the monocular region as the *informational eye*, and the eye contributing the background and border as the *noninformational eye*.

Binocular rivalry and the interocular inhibitory process of suppression due to rivalry may be a reasonable explanation for luning and fragmentation. There are different varieties of binocular rivalry including piecemeal dominance, binocular superimposition, and binocular transparency (see Yang, Rose and Blake, 1992), all of which may contribute to fragmentation. Binocular transparency describes both dichoptic stimuli being seen simultaneously, but appearing "scissioned" or segregated in depth. Superimposition is when they appear to occupy the same space and piecemeal dominance refers to small isolated parts of each eye's image dominating the binocular percept.

Purpose of study

The current investigation was designed to determine how fragmentation of a binocular FOV is influenced by display factors. One factor is the way in which the partial binocular overlap display is presented. A partial binocular overlap display can be presented in either the divergent display mode or the convergent display mode. In the divergent display mode, the right eye's monocular region is to the right of the binocular overlap region; that is, the right eye exclusively sees the portion of the visual world to the right of the portion seen by both eyes. Similarly, the left eye's monocular region is to the left of the binocular overlap region. Conversely, in the convergent display mode the right eye's monocular region is to the left of the binocular overlap region, and the left eye's monocular region is now to the right of the binocular overlap region. This would occur if one were binocularly viewing the visual world through an aperture. Good discussions of the visual geometry ecologically corresponding to these display modes can be found in Shimojo and Nakayama (1990) and Barrand (1979). Melzer and Moffitt (1991) and Klymenko et al., (in preparation) have shown that the convergent display mode induces less luning than the divergent display mode. The other factor is the visual dimension

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factor, which refers to the sizes of the various visual areas. There were four visual dimension factors; these were the sizes of the monocular regions, the sizes of the monocular fields, the size of the binocular FOV, and the size of the binocular overlap region. Our main purpose was to test the influence of the size of the different visual areas on fragmentation of the display. We did this by systematically varying the sizes of these areas to see how this affected fragmentation.

In summary, we tested the effect on fragmentation of (1) the display mode factor, and (2) the visual areas, referred to here as the visual dimension factors. We did this by direct comparison between pairs of minimally different stimuli.

Method

Subjects

Thirteen Army aviation student volunteers, twelve males and one female, took part in the experiment. Army aviation students are a population which has undergone rigorous vision screening. All had 20/20 unaided or better Snellen acuity. Each subject's vision was checked before the experiment using the standard Armed Forces Vision Tester. Also, the accommodative/convergence relationship and the interpupillary distance (IPD) of each subject were measured and recorded. A copy of the exam data sheet is included in Appendix A. The average age of the subjects was 26. The age range was 19 to 29.

Equipment

The equipment consisted of three major components: A Hewlett Packard HP-98731 Turbo-SRX computer graphics workstation used to generate the visual stimuli; a custom optical table configuration used to optically direct the visual stimuli from the workstation monitor to a pair of Adlerblick viewing binoculars (Edmund Scientific); and a subject booth.[1] The booth was a lightproof enclosure behind the binoculars, where the subject viewed the stimuli via the binoculars and responded via an HP response keypad or "button-box."

The HP-98731 Turbo-SRX computer graphics workstation consisted of a 19-inch color Trinitron monitor (1280 x 1024 pixels) for presenting visual stimuli, and a computer for generating the stimuli and for recording the responses and analyzing the data. Connected to the workstation were: the experimenter's terminal to allow the experimenter to run the experimental programs and monitor the progress of each experimental session; an external monitor tied to the HP computer via a scan converter to allow the experimenter to unobtrusively view the experimental stimuli presented to the subject; and the button-box, a 32-button keypad to allow the subject to respond to the visual stimulus presentations.
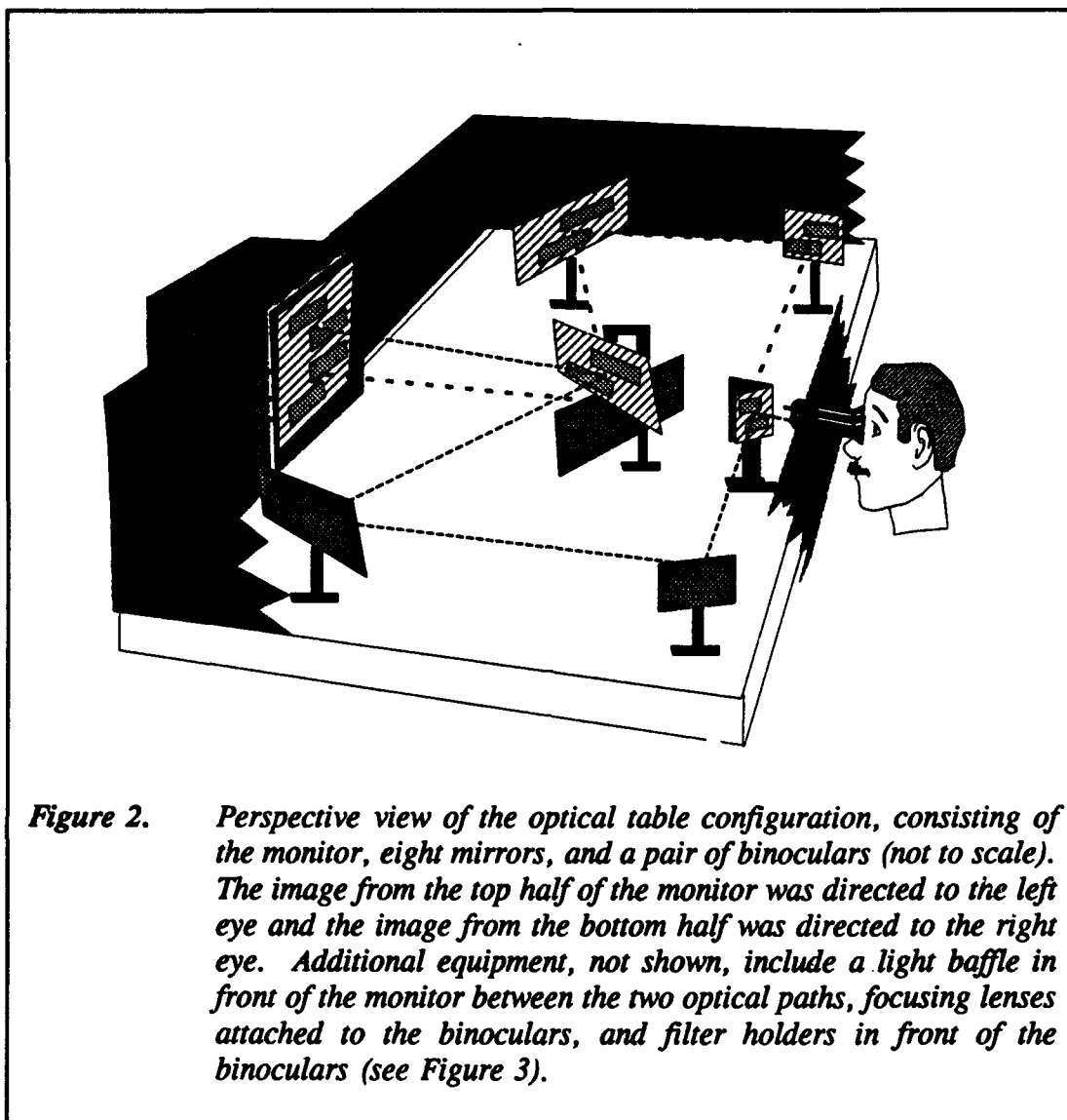
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[1] See Manufacturers' list in Appendix B.

The optical table configuration consisted of a 4 foot x 6 foot optical table with the workstation monitor mounted at one wide end of the table and eight front surfaced mirrors mounted on the table to direct the visual image — the optical train — to a pair of viewing binoculars mounted on the other wide end of the table (see Figures 2 and 3). The purpose of the eight mirrors was to allow the independent presentation of two channels, one to each ocular of the binoculars from the same monitor. Through the binoculars, the image on the top half of the monitor was seen by the left eye and the image on the bottom half of the monitor was seen by the right eye. The 7x50 binoculars were mounted within a fixture which allowed IPD to be precisely adjusted for each subject. Affixed on the front of the binoculars were auxiliary focusing lenses to focus the magnified image for the optical train viewing distance. A light baffle in front of the monitor between the two optical paths was positioned to prevent cross talk between the two image channels. Filter holders in front of the binoculars allowed the placement of neutral density optical filters. The two mirrors (L4 and R4 in Figure 3) mounted directly in front of the binoculars were movable to allow adjustments corresponding to the IPD settings of the binoculars. These adjustments to the distance between L4 and L3, and R4 and R3 ensured a properly centered image for each IPD setting.

The optical table configuration was designed to allow the horizontal extent of the monitor (1280 pixels) to match the horizontal visual extent (diameter) of each ocular of the binoculars. The resulting images seen through each ocular of the binoculars were 50 degrees of visual angle corresponding to 1280 pixels, or 25.6 pixels per degree of visual angle. The temporal resolution, or frame rate of the monitor, was 60 Hz noninterlaced, and the luminance ranged from 0.02 to 10.0 foot-Lamberts. The 7x50 Adlerblick binoculars had a vertex distance of 27 mm and an exit pupil diameter of 7.14 mm.

The convex cylindrical surface of the monitor (approximately 1.5 meter radius of curvature) resulted in a focal distance disparity for the center and edges of the display seen through the binoculars. The focusing difference between the center and extreme edge of the image on the monitor, measured with a diopterscope, was approximately 0.75 diopters. To ensure a clear image for the test stimuli within the FOV used, the binoculars were focused with the diopterscope to 0.50 diopters (2 meters) for the center of the display. This ensured that subjects, all younger than 30 years of age, could easily accommodate to any part of the visible image.

Covering the optical table and the subject booth was a metal frame covered by black cloth to prevent light leakage and to protect the optical table components. The subject booth was a lightproof enclosure in which the subject was seated at an adjustable chin rest affixed in front of the binoculars. Except for the stimuli viewed through the binoculars, the subject was in darkness. Mounted on the end of the optical table in front of the subject was a call switch which

Figure 2. *Perspective view of the optical table configuration, consisting of the monitor, eight mirrors, and a pair of binoculars (not to scale). The image from the top half of the monitor was directed to the left eye and the image from the bottom half was directed to the right eye. Additional equipment, not shown, include a light baffle in front of the monitor between the two optical paths, focusing lenses attached to the binoculars, and filter holders in front of the binoculars (see Figure 3).*

rang a buzzer. Mounted within easy access of the subject was the button-box used to register the subject's responses. Above the subject was an adjustable air vent connected to the air conditioning to allow the subject control of the temperature in the subject booth.

Stimuli

There were two types of stimulus factors, one being the display mode factor — convergence versus divergence, and the other being the visual dimension factor. There were four visual dimension factors; these were the sizes of the monocular regions, the sizes of the monocular fields, the size of the binocular FOV, and the size of the binocular overlap region.

Monitor

6'

13.5"

L2 *

30°   60°
60° 60°

R2 **

L1 **   30°   R1

L4   R4

45°   45°

L3   R3

← Filters

Focusing
lenses

IPD

* Mirrors tilted -2.4° from vertical
** Mirrors tilted +2.4° from vertical

Figure 3. *Top view of the optical table configuration. The image from the top half of the monitor (solid rays) is reflected down from mirror L1 to L2, and then parallel to the surface of the table, from mirrors L2 to L3 to L4 to the left ocular of the binoculars. Similarly for the right channel, the image from the bottom half of the monitor (dashed rays) is reflected up from mirror R1 to R2, and then parallel to the surface of the table from mirrors R2 to R3 to R4 to the right ocular of the binoculars. The binoculars and movable mirrors L4 and R4 are set to correspond to each individual subjects's interpupillary distance. The resulting stimulus is shown in Figure 4.*

The display mode factor was independent of the visual dimension factors, while the visual dimension factors were co-determined as described in the design section. Each of the five experiments contained both convergent and divergent versions of each stimulus pattern. Each experiment differed in the stimulus factors which were varied in the pairs of stimuli presented in each of the experimental displays.

Two stimuli, designated the baseline stimuli, had mean values on all the visual dimensions. The baseline stimuli were common to each of the five experiments. Additional

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stimuli were generated by varying the four visual dimension factors with reference to the baseline stimuli. These factors were increased and decreased with reference to the baseline stimuli and were designated as C1 and C3 for the convergent versions and D1 and D3 for the divergent versions. They are described in the design section. Below we describe the baseline convergent and divergent stimuli designated as C2 and D2, respectively.

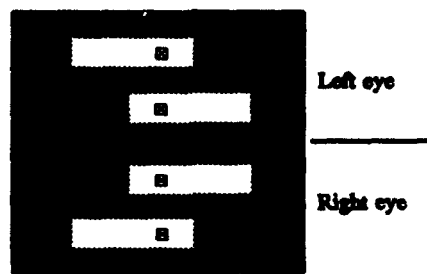Baseline convergent and divergent binocular overlap display modes

The visual field of each eye's view through the binoculars consisted of a gray rectangle against a black background. The grey rectangle subtended of visual angle of 15.6 degrees of visual angle (400 pixels horizontal) x 3.9 degrees (100 pixels vertical). In each circular (50 degrees diameter) ocular view through the binoculars, the two rectangles for each display mode were centrally located in the vertical dimension and horizontally located as described below. These rectangles represent each eye's monocular field, and the horizontal relationship between them defines the display mode (see Figure 4). The luminance through the binoculars of the rectangular fields was approximately 2.0 foot-Lamberts against a dark background of 0.02 foot-Lamberts.

When the rectangles were each centrally located so that there was full overlap of each of the monocular fields, the total horizontal FOV was 15.6 degrees, the same as each monocular field. This full overlap display mode was considered the reference position.

When the rectangular field for the right eye was moved 3.9 degrees to the right of the reference position and the rectangular field for the left eye was moved 3.9 degrees to the left of the reference position, the monocular fields remained the same in extent, but the total FOV was increased to 23.4 degrees, where both eyes saw a smaller central binocular overlap region of 7.8 degrees and each eye saw a flanking monocular region of 7.8 degrees. Because the right eye saw the flanking monocular region to the right of the binocular region, and the left eye saw a flanking monocular region to the left of the binocular region, the display mode was divergent, which except for the sizes of the visual regions is what is seen in normal human vision.

Conversely, if the rectangular field for the right eye was moved 3.9 degrees to the left of the reference position and the field for the left eye was moved 3.9 degrees to the right of the reference position, then the display mode was convergent, where both eyes again saw the same smaller central binocular region of 7.8 degrees. The total FOV was again increased to 23.4 degrees, but this time the right eye's flanking monocular region was to the left of the binocular region, and conversely the left eye's flanking monocular region will be to the right of the binocular region. This can be simulated by looking through an aperture.

This pair of stimuli — the convergent and divergent versions of the baseline stimulus — constituted the stimulus set for Experiment 1. Table 1 gives the values of the four visual dimension factors of the baseline stimulus. These values are the intermediate values of the four visual dimension factors in all five experiments collectively and individually. Experiments 2-5

Rectangular monocular fields
on the monitor
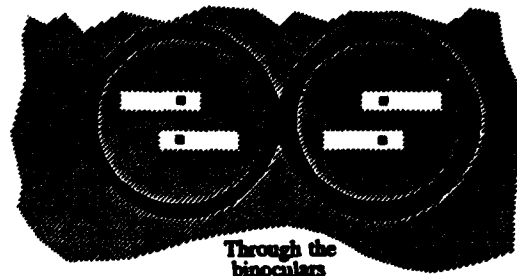
Through the
binoculars
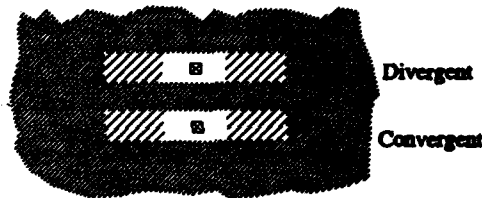
Fields-of-view as
seen by the observer
when properly fused

Figure 4. *An illustration of a stimulus pair — the baseline convergent and divergent display modes — presented for simultaneous comparison. The top panel shows the rectangular monocular fields on the monitor and indicates the destination eyes. The middle panel shows the monocular fields through the binoculars, and the bottom panel shows the two fields-of-view as experienced by the subject when the display is properly fused. The two display modes indicated in the bottom panel are similar in every respect, except for the regions of the retinas stimulated. The shading in the two fields-of-view in the bottom panel indicates areas of dichoptic competition which can cause fragmentation of each field-of-view into three phenomenally distinct regions. The crossed squares in the monocular fields serve as fusion locks and fixation markers.*

Table 1.

Size of visual areas in degrees of visual angle.

Visual dimension factor

Experiment	Stimuli	(A) Monocular regions		(B) Monocular fields		(C) Field-of-view		(D) Binocular overlap region	
1	C2, D2	7.8	2	15.6	4	23.4	6	7.8	2
2	C1, D1	7.8	2	11.7	3	19.5	5	3.9	1
	C2, D2	7.8	2	15.6	4	23.4	6	7.8	2
	C3, D3	7.8	2	19.5	5	27.3	7	11.7	3
3	C1, D1	16.7	3	15.6	4	27.3	7	3.9	1
	C2, D2	7.8	2	15.6	4	23.4	6	7.8	2
	C3, D3	3.9	1	15.6	4	19.5	5	11.7	3
4	C1, D1	9.8	2.5	13.7	3.5	23.4	6	3.9	1
	C2, D2	7.8	2	15.6	4	23.4	6	7.8	2
	C3, D3	5.9	1.5	17.6	4.5	23.4	6	11.7	3
5	C1, D1	5.9	1.5	13.7	3.5	19.5	5	7.8	2
	C2, D2	7.8	2	15.6	4	23.4	6	7.8	2
	C3, D3	9.8	2.5	17.6	4.5	27.3	7	7.8	2

First column under each visual dimension factor is the horizontal extent of the visual area in degrees of visual angle. Second column represents relative size of areas for easier comparison, where unity equals 100 pixels or 3.9 degrees. The baseline stimuli, C2 and D2, were the same in each experiment. Remaining stimuli varied according to experiment.

included stimuli, in addition to the baseline stimuli, in which the visual dimension factors were both increased and decreased with respect to the baseline stimulus values as described in the design section and shown in Table 1 and Figure 5.

Each experimental display condition had a pair of stimulus patterns, where these were centered 5 degrees of visual angle (256 pixels) above and below the center of the display (see Figure 4). The particular combinations of stimulus pairs are described in the design section.

Fusion locks

Simply shifting the images as described above is no guarantee that subjects will binocularly fuse the images. Subjects need similar stimuli common to both eyes to prevent disjunctive eye movements in order to binocularly fuse images properly and to avoid image slippage, which leads to the binocular overlap of inappropriate regions of the two monocular images. To ensure "binocular locking" of the appropriate areas of the monocular fields, a fusion lock was always present in each eye's image in the binocular region. These are the 25 x 25 pixel (0.98 x 0.98 degrees of visual angle) black outline squares, with diagonal lines connecting the opposite corners, located in the image as shown in the rectangular fields in Figure 4. The fusion locks were appropriately located in each monocular field so as to be centered in the binocular overlap region.

Optical convergence

Optical convergence here refers to the angle between the optical axes of the eyes and should not be confused with the convergent display mode. Accommodation can induce optical convergence demands to match the implied distance of an image. A variety of visual discomforts and problems can result if accommodation and optical convergence are mismatched. For our equipment, optical convergence and accommodation were both set for 2 meters at the center of the display. Since the centers of both the right eye and the left eye images were focused to 2 meters (0.50 diopters) through the binoculars, the right and left images were also positioned so that the eyes converged to 2 meters (i.e., for an average subject with an IPD separation of 64 mm). Convergence was induced by shifting each eye's image on the monitor 0.92 degrees of visual angle (22 pixels) in the nasal direction. The range of IPDs for the 13 subjects was 60-69 mm, with a mean of 64 mm. For this group of subjects, the fixed convergence induced convergence demands of from 1.88 meters (for a 60 mm IPD) to 2.15 meters (for a 69 mm IPD). This is less than 0.3 prism diopters (3 milliradians) of residual fusional convergence or divergence required for an image located at 2 meters.

Design

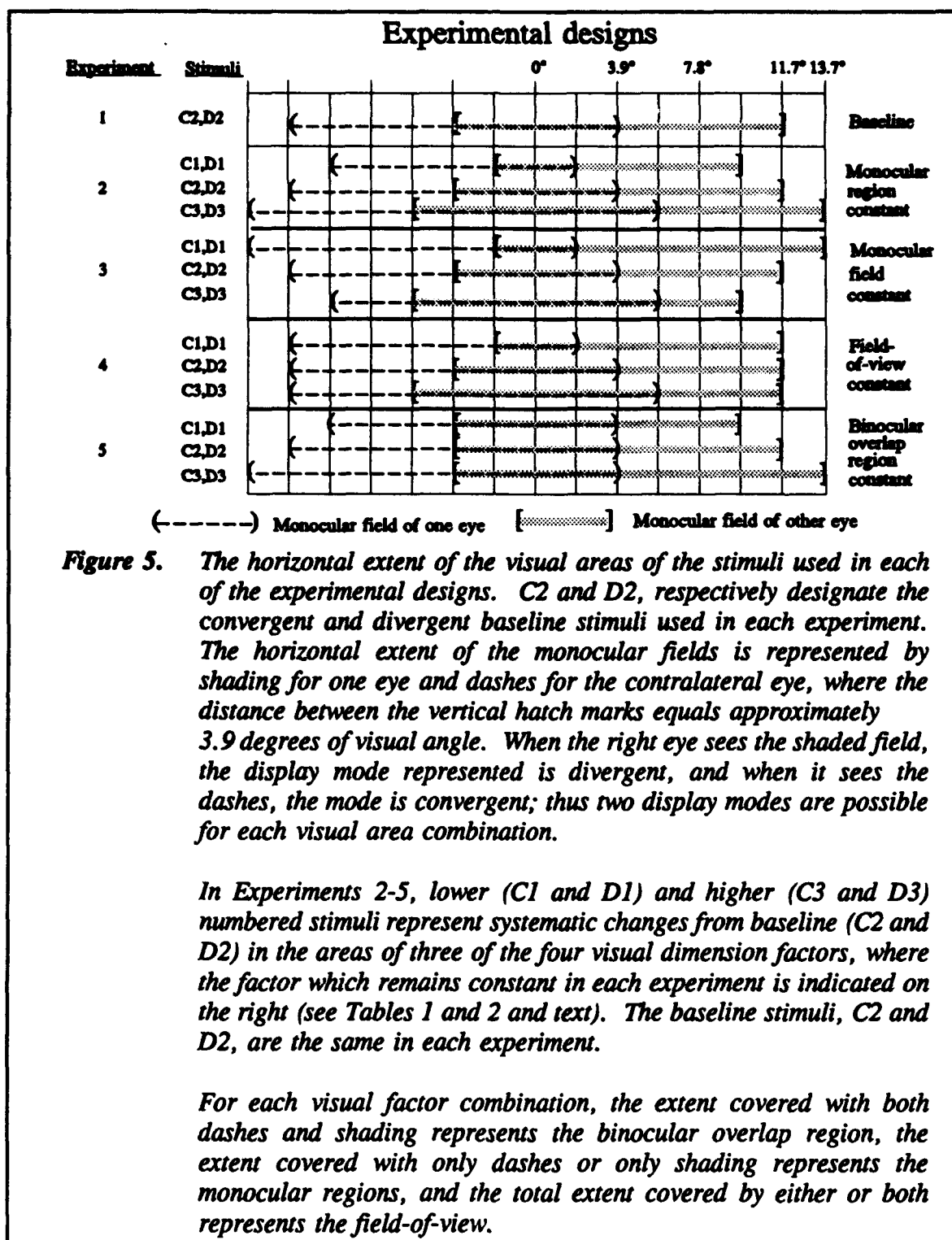### Visual geometric constraints and relative size

Five visual factors were tested. One was the display mode factor, which could be convergent or divergent. Each of the five experiments tested this factor. The display mode factor was independent of the other four factors, which were the visual dimension factors. These were the sizes or visual angles of (A) the monocular regions, (B) the monocular fields, (C) the total FOV, and (D) the binocular overlap region. The display mode factor could be varied independently of the visual dimension factors. The four visual dimension factors were co-dependent. When one of the visual dimension factors was varied, i.e., increased or decreased in visual angle, at least two of the other factors would also change in visual angle because of the logical constraints of visual geometry. Only one visual dimension factor could be held constant if any of the other three were changed. When one factor was held constant and the second was changed, the direction of the changes in the third and fourth factors were determined. Table 2 indicates the combinatorial possibilities based on the constraints of visual geometry when one factor was held constant, which Figure 5 shows graphically.

Experiments

In an experimental design testing four factors, a typical approach might be to vary only one factor per experiment, holding the other three factors constant in order to infer the unique effect of that factor. Because of the geometric constraints, we defined Experiments 2-5 by which factor was held constant rather than varied. Experiments 2-5 exhaust all combinatorial possibilities for varying the four visual dimension factors when one of the factors is held constant. The baseline conditions used in Experiment 1 were used in Experiments 2-5. The visual angles on all four visual dimension factors in the baseline stimulus were the intermediate and mean value of the visual angles used in all the experiments.

There were six stimuli each in Experiments 2-5. In each of these experiments, two of the stimuli were the convergent and divergent versions of the baseline stimulus designated as C2 and D2.

In Experiment 2, the size of the monocular region was held constant. Four additional stimuli were created by increasing and decreasing the size of one of the three remaining visual dimension factors for both the convergent and divergent display modes creating a set of six stimuli. The two remaining visual dimension factors covaried with these changes in a fixed manner. We arbitrarily designated a change in one direction from the baseline, C2 and D2, as C1 and D1 and the change in the other direction as C3 and D3, the convergent and divergent versions being, respectively, the C and the D stimuli.

Figure 5. The horizontal extent of the visual areas of the stimuli used in each of the experimental designs. C2 and D2, respectively designate the convergent and divergent baseline stimuli used in each experiment. The horizontal extent of the monocular fields is represented by shading for one eye and dashes for the contralateral eye, where the distance between the vertical hatch marks equals approximately 3.9 degrees of visual angle. When the right eye sees the shaded field, the display mode represented is divergent, and when it sees the dashes, the mode is convergent; thus two display modes are possible for each visual area combination.

In Experiments 2-5, lower (C1 and D1) and higher (C3 and D3) numbered stimuli represent systematic changes from baseline (C2 and D2) in the areas of three of the four visual dimension factors, where the factor which remains constant in each experiment is indicated on the right (see Tables 1 and 2 and text). The baseline stimuli, C2 and D2, are the same in each experiment.

For each visual factor combination, the extent covered with both dashes and shading represents the binocular overlap region, the extent covered with only dashes or only shading represents the monocular regions, and the total extent covered by either or both represents the field-of-view.

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Table 2.
Stimulus set of visual area changes

Visual dimension factor	Experiment 2		Experiment 3		Experiment 4		Experiment 5	
A. Monocular region	0	0	+	—	+	—	—	+
B. Monocular field	—	+	0	0	—	+	—	+
C. Field-of-view	—	+	+	—	0	0	—	+
D. Binocular overlap region	—	+	—	+	—	+	0	0

If the size of any visual dimension factor is held constant (0) and the size of any second factor is changed by an increase (+) or by a decrease (-) in visual angle, then the directions of change of the remaining two factors are fixed. The eight columns represent all the possible combinations of changes due to the constraints of visual geometry when one factor is held constant, where the first and second column under each experiment represent opposite directions of change. Each experiment is defined by which factor is held constant. By convention, under each experiment the first column represents the C1 and D1 stimuli and the second column represents the C3 and D3 stimuli with reference to the baseline stimuli (C2 and D2) (see text).

Of these six stimuli in Experiment 2, six stimulus pairs were generated in order to allow the subject to make direct comparisons. There were two stimulus pairs within the convergent mode (C1 vs. C2, C2 vs. C3), and two within the divergent mode (D1 vs. D2, D2 vs. D3). These four pairs assessed the effect of varying visual dimension factors, with display mode and size of monocular regions held constant. The two remaining pairs tested only the effect of display mode for both the number 1 and number 3 stimuli (C1 vs. D1, C3 vs. D3). The one remaining pair testing display mode (C2 vs. D2) for the baseline stimuli was the pair already tested in Experiment 1.

Experiments 3, 4 and 5 differed from Experiment 2 only in that a different visual dimension factor was held constant. In Experiment 3, the size of the monocular fields was held constant, while in Experiments 4 and 5 the size of the field-of-view and of the binocular overlap region, respectively, was held constant. The intermediate sized stimuli in Experiments 2-5 were the same baseline stimuli, C2 and D2. These were paired in Experiment 1, although this comparison can be considered as part of the matrix of Experiments 2-5 (see Tables 1 and 2). Thus, each pair of stimuli tested differed on either the display mode factor or the visual dimension factors, in which case one of the visual dimensions was held constant. Each stimulus pair had two positional variations to counterbalance top and bottom positions for the two stimuli in each pair.

In summary, there were five experiments, where the stimuli in Experiment 1 consisted of the baseline stimulus pair, and the stimuli in the remaining four experiments consisted of 6 stimulus pairs each, for a total of 25 stimulus pairs. These 25 stimulus pairs were the

experimental conditions which were presented in a single session. The 50 stimulus combinations (25 stimulus pairs x 2 positions) were presented in random order within 4 blocks for a total of 200 trials for each subject (25 stimulus pairs x 2 positional variations x 4 blocks).

Procedure

Each subject was required to read and sign a volunteer consent form before the verbal instructions were given, explaining the task and the use of the button-box. In each experimental session, the subjects were seated in the subject booth where they viewed the computer generated stimuli through a set of binoculars. The binoculars and movable mirrors, L4 and R4, were individually positioned to correspond to each subject's IPD. Each subject's head and eye were properly positioned by displaying an alignment pattern, a square grid which covered the entire extent of the screen, to ensure that the subject could see the entire FOV through the binoculars. The subject was first given practice in obtaining binocular fusion and in the use of the button box and was given a brief practice session with four or five stimuli to make sure the instructions were understood. Each of the subjects had experience with the experimental setup from a previous study measuring visual thresholds.

Experimental session

For the experimental session, each subject was instructed to indicate via the button-box which of the two patterns of the stimulus pair — the upper or the lower one — appeared more like a single and unitary region or surface, i.e., had less of a tendency to fragment or segregate into a central region and two side regions. The more fragmentary pattern was the one which had more of a tendency to appear to consist of more than one surface. They were told to look at the fusion lock, which acted as a fixation marker, when judging a stimulus pattern. They also were told they could look up and down between the fusion locks as often as they wished for as long as they wished to make the comparison between the two patterns. They were cautioned to ignore the size of the regions in making their judgments and to respond only when they were properly fused, which was indicated by a single fusion lock in each stimulus pattern. All subjects completed the session within 45 minutes.

Each subject was instructed that, if at any time during the presentation of a stimulus, fusion was lost and diplopia resulted, which would be indicated by the presence of more than one fusion lock pattern in each stimulus, the experimenter was to be told. The experimenter then would talk the subject through a number of visual techniques until fusion was regained.

Data analysis

There were two types of factors: (1) the visual display mode factor, which tested the convergent versus the divergent mode, and (2) the visual dimension factors, which varied as described previously. There was one stimulus pair tested in Experiment 1, and six in each of

Experiments 2-5, four of which tested visual dimension factors. These four tested directional changes (some factors increased and some decreased). For the visual dimension factors in Experiments 2-5, an overall one-sample t-test (two-sided) first tested the effect between all higher and all lower numbered stimuli, where each subject's score was the mean of the four visual dimension factor comparisons consisting of a total of 32 trials (2 positions x 4 blocks x 4 comparisons). This test compared the obtained mean percent (average over subjects) with the expected null value of 50 percent for no difference in fragmentation judgments. We also tested each individual paired comparison (shown in the Results section). Each stimulus pair was viewed eight times by each subject as part of the randomized design (2 positional variations x 4 blocks), where each subject's score was the mean of the eight trials. For each individual comparison, a one-sample t-test (two-sided) compared the obtained mean percent (average over subjects) with the expected null value of 50 percent for no difference in fragmentation (Winer, 1971).

As a check on the data, we also employed the nonparametric one-sample Kolmogorov-Smirnov maximum deviation statistic for each individual comparison (Bradley, 1968; Goodman, 1954). This tested the obtained distribution of subject percentages, where each subject could score between zero and a 100 percent. This was tested against the expected distribution of random responses, which was the binomial distribution with nine possible outcomes ([0/8 to 8/8] x 100), where the expected mean was 50. The results of the nonparametric tests were in accord and reported with the parametric tests in the figures presented in the Results section.

Results and discussion

Reports by the subjects and informal observations indicated a number of phenomenal differences to explain why one pattern was judged as fragmenting more than another. For example, in one stimulus pattern the binocular overlap border may have tended to be phenomenally more visible and therefore it segregated the monocular and binocular regions more thoroughly; or, the monocular regions may have appeared different in brightness than the binocular overlap region; or, the monocular regions may have had more of a tendency to appear to lie in a different depth plane; or, the monocular regions may have appeared to disappear more often or more completely. Indeed, the monocular regions would often disappear completely in the divergent displays illustrating a stronger, more thorough version of the darkening luning effect emanating from the binocular overlap border. Whatever the subjective impression, the appearance of the monocular regions was no doubt the result of the dichoptic competition between the two eyes, where the monocular region is the result of the binocular combination of the monocular field of the informational eye with the background and monocular field border of the contralateral noninformational eye. Depending on a number of factors, including luminance levels, this binocular combination can result in either summation or averaging of the brightness and contrast of the two images, or in a percept between the average and the sum (Curtis and Rule, 1980; DaSilva and Bartley, 1930; Engel, 1967; Legge and Rubin, 1981; Blake and Fox, 1973; Blake and Sloane, 1981); or the combination will result in binocular rivalry and suppression, with one eye's image dominating the percept.

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When the informational eye contributing the monocular field to the monocular region dominates, the result is a unitary or stable appearance of the FOV, where the monocular region appears to be a continuation of the binocular overlap region. When the noninformational eye (contributing the background and border to the monocular region) dominates or contributes significantly to the binocular percept, the result is a fragmented or segregated appearance of the FOV, where the monocular region appears to be different than the binocular overlap region. The appearance of the border in the FOV contributes to the separation of the monocular region, and dominance by, or averaging with, the background contributes to the dissimilarity in appearance of the monocular regions (i.e., the fragmentation of the FOV). Our experiments measured how the relative areas of each of the four visual dimension factors affected the dichoptic competition between the two eyes in determining the phenomenal binocular appearance of the FOV. The experiments also independently tested the display mode factor.

The results are given in Figures 6-10 and Table 3. In the figures, the member of each stimulus pair at the tail end of the connecting arrows was judged to be more fragmentary (or less unitary). The mean percentages of the number of times the pair member at the base was judged to be more fragmentary are next to the arrows. (This number also indicates the percentage of time the member at the head of the arrows was judged as appearing more unitary, where 50 percent would indicate equality between pair members.) In parentheses, on the other side of each of the connecting arrows, are the results of the one-sample t-test (left), and of the nonparametric Kolmogorov-Smirnov one-sample test (right). The form of the connecting arrows indicates the significance level of the t-test (two-sided). The significance levels of the Kolmogorov-Smirnov tests are not separately indicated as they parallel those of the t-tests. The vertical connecting arrows in each figure represent comparisons between display modes, where the values of the visual dimension factors are the same. The horizontal connecting arrows represent comparisons between stimuli differing in visual dimension factors, where the display mode is the same.

Experiment 1: Replication of display mode effect

The divergent member of the baseline pair was judged as more fragmentary 93.3 percent of the time (compared to 6.7 percent for the convergent member). The difference, 93.3 minus the expected value of 50.0 for no difference, was highly significant as indicated in Figure 6. This replicates previous findings on the effect of display mode on luning (Melzer and Moffitt, 1991; Klymenko et al., in preparation).

Previous studies, using as a measure the percentage of time out of the total stimulus duration time that luning was seen (Melzer and Moffitt, 1991, Klymenko et al., in preparation) found that for a number of conditions, the divergent display mode systematically induced more luning than the convergent mode. The current study differed from the previous two studies in that subjects made forced-choice direct comparisons between stimuli that were simultaneously present without time limitations rather than viewing sequentially presented stimuli each for a

Table 3.
Summary of visual dimension factor results

| Experiment	Factors tested			->	Results
2		- B - C	- D	->	+ F
		+ B + C	+ D	->	- F
3	+ A	+ C	- D	->	+ F
	- A	- C	+ D	->	- F
4	+ A - B		- D	->	+ F
	- A + B		+ D	->	- F
5	- A - B - C			->	0
	+ A + B + C			->	0

The combined results of the effect of the visual dimension factors on fragmentation: (A) the size of the monocular regions, (B) the size of the monocular fields, (C) the size of the field-of-view, and (D) the size of the binocular overlap region. Each experiment tested different combinations of increases (+) and decreases (-) in the areas of these factors as indicated, where the increases and decreases were tested against the same baseline condition in each experiment. This resulted in either more (+F) or less (-F) fragmentation or no change (0) as indicated on the right. The binocular overlap region (D) is the only factor consistently correlated with the fragmentation of the image.

fixed amount of time. Another methodological difference was having the subjects judge the unitary-fragmentation aspect of the FOV of the stimuli rather than the presence of luning per se. The results from both methods, however, are in accord. The basis of both luning and fragmentation is likely the dichoptic competition between the two eyes. For each monocular region, the noninformational eye containing the background and the monocular border compete binocularly with the informational eye containing the homogeneous monocular field. The noninformational eye is a relatively stronger competitor in the divergent than in the convergent display mode. Between these two display modes, all other factors other than the location of the monocular fields on the retina are equal, which likely leads to a sensory-physiological basis for this difference. The possible reasons for this divergent display inferiority (i.e., more fragmentation and luning) are discussed after the following visual dimension factor results.

Experiment 2: Monocular region held constant

For the six stimuli of Experiment 2, the size of the monocular regions (factor A) was held constant to the baseline level. For the lower numbered stimuli, C1 and D1, the sizes of the monocular fields (B), the FOV (C) and the binocular overlap region (D) were decreased from baseline, as indicated in Figure 5 and Table 2. Conversely, for the higher numbered stimuli, C3 and D3, the sizes of factors B, C and D were increased.
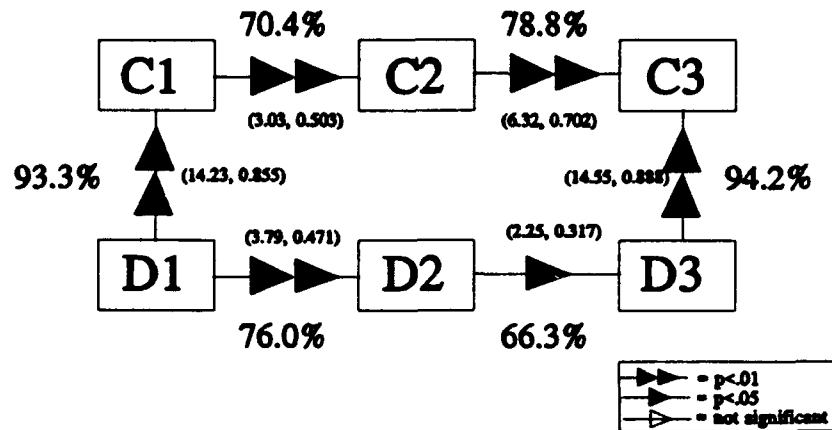
21
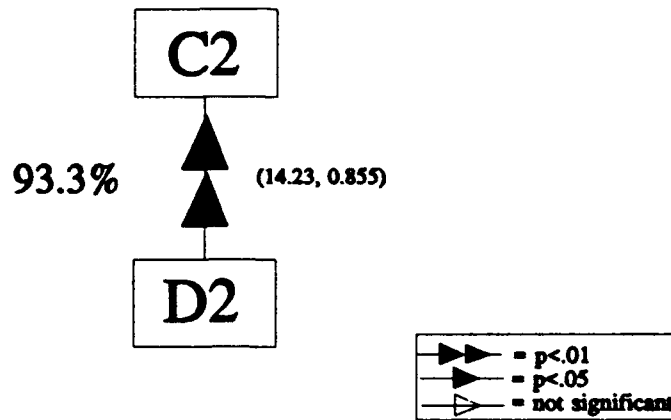
Figure 6. *Stimulus pair tested is connected by arrows with the more fragmentary stimulus at the base of the arrows. Mean percentage of the number of trials the stimulus at the base was judged to be more fragmentary is shown on the left side with the results of the one-sample t-test and the one-sample Kolmogorov-Smirnov test in parentheses on the other side. The significance level of the t-test is shown as indicated by the arrow symbols.*

Overall, the mean percentage of fragmentation judgments was 73.8 percent (SD = 19.3) with lower numbered stimuli being judged as more fragmentary than higher numbered stimuli; this overall effect of changing the visual dimension factors was significant, $t(12) = 4.44$, $p < 0.001$. The results are shown in Figure 7, where the six stimuli are arrayed with the six individual comparisons indicated by connecting arrows. The mean percentages of fragmentation judgments for each paired comparison are shown outside the array; inside are the results of the associated statistical tests. The significance levels and the direction of increased fragmentation are indicated by the arrows. For the individual comparisons, testing pairs differing in the sizes of the visual dimensions (indicated by the horizontal arrows in Figure 7), one can see that when the three visual dimension factors B, C, and D are simultaneously decreased — the left side of Figure 7 — fragmentation increases, and when these visual dimension factors are increased — the right side of Figure 7 — fragmentation decreases. This is true whether the pairs are convergent or divergent. These results are summarized in the first two rows of Table 3. Which of these visual dimension factors are most important will be seen in the results of the following experiments, where the sizes of the visual dimension factors were changed simultaneously in different directions.

In both the pairs comparing display mode (indicated by the vertical arrows in Figure 7), the divergent member was reported more fragmentary significantly in terms of percentage of

Results for Experiment 2: monocular region constant.

70.4%   78.8%

C1 ▶▶ C2 ▶▶ C3

(3.03, 0.505)   (6.32, 0.702)

93.3% ▲ (14.23, 0.855)   (14.55, 0.888) ▲ 94.2%

(3.79, 0.471)   (2.25, 0.317)

D1 ▶▶ D2 ▶ D3

76.0%   66.3%

▶▶ = p<.01
▶ = p<.05
▷ = not significant

Figure 7. *Stimulus pairs tested are connected by arrows with the more fragmentary stimulus at the base of the arrows. Mean percentage of the number of trials the stimulus at the base of the arrows was judged to be more fragmentary is shown on one side of the connecting arrows with the results of the one-sample t-test and the one-sample Kolmogorov-Smirnov test in parentheses on the other side of the connecting arrows. The significance level of the t-test is shown as indicated by the arrow symbols.*

time, lending further support to the inferiority of the divergent display mode for two new visual dimension conditions. (The baseline comparison, C2 vs. D2 was reported as Experiment 1, although logically it can be considered to be a part of any of the experiments.) This divergent display mode inferiority is replicated in each of the remaining experiments indicating that regardless of the tested sizes of the visual dimensions, when display mode is the only difference between stimuli, the divergent display mode will fragment more.

Experiment 3: Monocular field held constant

For the six stimuli of Experiment 3, the size of the monocular fields (factor B) was held constant to the baseline level. For the lower numbered stimuli, C1 and D1, the sizes of the monocular regions (A) and the FOV (C) were increased, and the size of the binocular overlap region (D) was decreased from baseline as indicated in Figure 5 and Table 2. Conversely, these size changes were reversed for the higher numbered stimuli, C3 and D3. The results for Experiment 3 are shown in Figure 8.
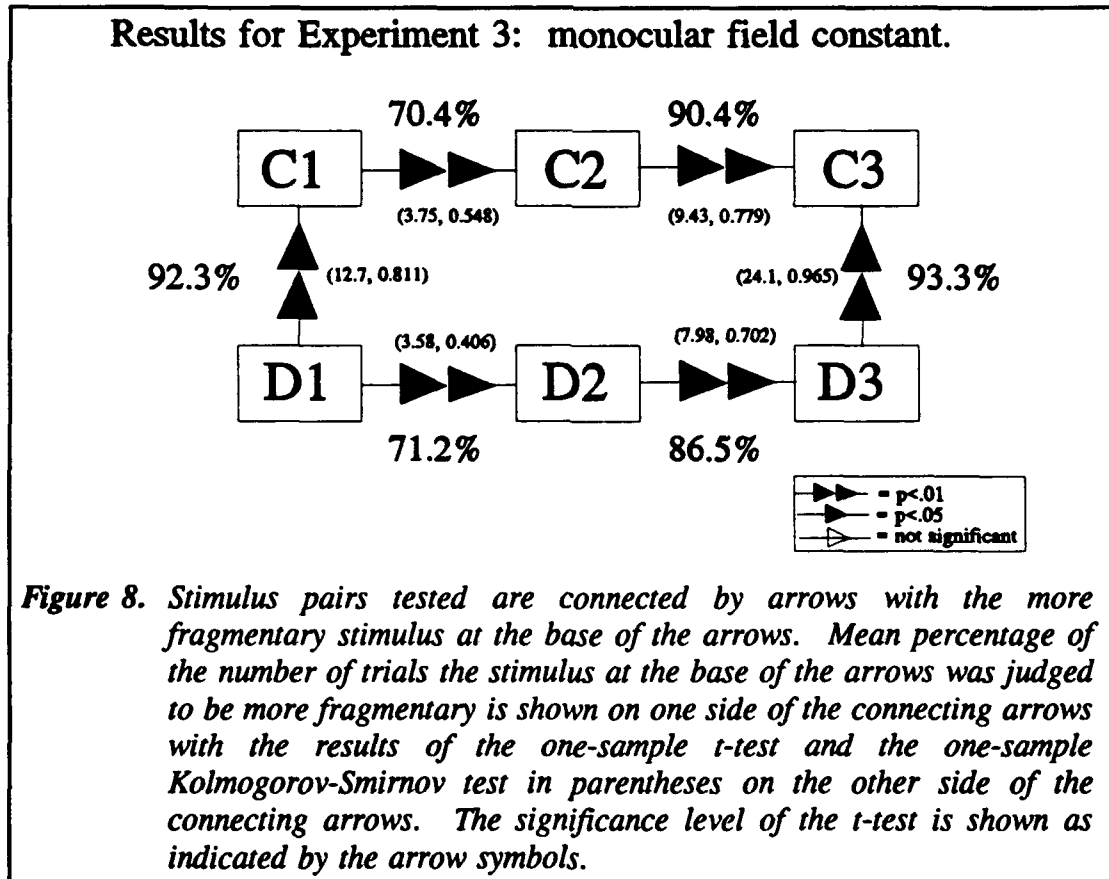
The overall mean percentage of fragmentation judgments was 80.5 percent (SD = 14.2) with lower numbered stimuli being judged as more fragmentary than higher numbered stimuli.

The overall effect of changing the visual dimension factors was highly significant, $t(12) = 7.77$, $p < 0.00001$. For the individual comparisons testing pairs differing in the sizes of the visual dimensions (indicated by the horizontal arrows in Figure 8), one can see fragmentation increased for lower numbered stimuli (where the size of the binocular overlap region was decreased) and decreased for higher numbered stimuli (where size of the binocular overlap region was increased) for both convergent and divergent pairs of stimuli. These results are summarized in the third and fourth rows of Table 3.
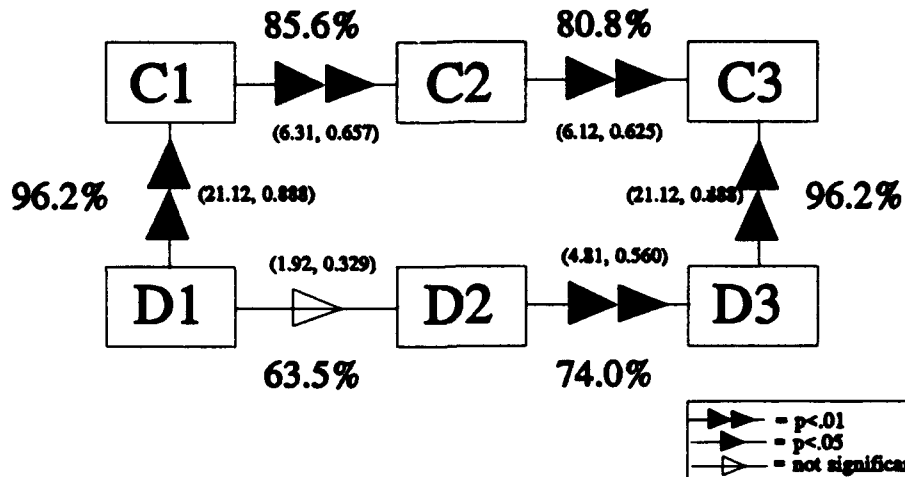
Again, as in Experiments 1 and 2, in both the pairs comparing the display modes (indicated by the vertical arrows in Figure 8), the divergent member was more fragmentary than the convergent member lending further support to the inferiority of the divergent display mode for two new visual dimension conditions.

<p align="center">Experiment 4: Total field-of-view held constant</p>

For the six stimuli of Experiment 4, the size of the FOV (factor C) was held constant to the baseline level. For the lower numbered stimuli C1 and D1, the sizes of the monocular regions (A) were increased, and the sizes of the monocular fields (B) and the binocular overlap region (D) were decreased from baseline, as indicated in Figure 5 and Table 2. Conversely, these size changes were reversed for the higher numbered stimuli C3 and D3. The results for Experiment 4 are shown in Figure 9.

Figure 8. Stimulus pairs tested are connected by arrows with the more fragmentary stimulus at the base of the arrows. Mean percentage of the number of trials the stimulus at the base of the arrows was judged to be more fragmentary is shown on one side of the connecting arrows with the results of the one-sample t-test and the one-sample Kolmogorov-Smirnov test in parentheses on the other side of the connecting arrows. The significance level of the t-test is shown as indicated by the arrow symbols.

Results for Experiment 4: field-of-view constant.

85.6%
80.8%

C1 ▶▶ C2 ▶▶ C3

(6.31, 0.657)   (6.12, 0.625)

96.2%   (21.12, 0.888)   (21.12, 0.888)   96.2%

(1.92, 0.329)   (4.81, 0.560)

D1 ▷ D2 ▶▶ D3
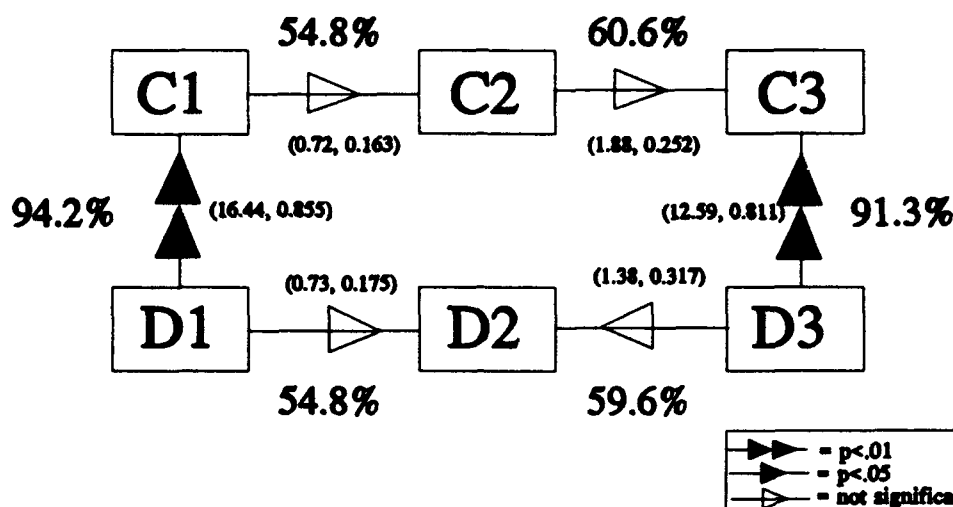
63.5%   74.0%

▶▶ = p<.01
▶ = p<.05
▷ = not significant

Figure 9. *Stimulus pairs tested are connected by arrows with the more fragmentary stimulus at the base of the arrows. Mean percentage of the number of trials the stimulus at the base of the arrows was judged to be more fragmentary is shown on one side of the connecting arrows with the results of the one-sample t-test and the one-sample Kolmogorov-Smirnov test in parentheses on the other side of the connecting arrows. The significance level of the t-test is shown as indicated by the arrow symbols.*

The overall mean percentage of fragmentation judgments was 76.0 percent (SD = 14.4) with lower numbered stimuli being judged as more fragmentary than higher numbered stimuli and the overall effect of changing the visual dimension factors was highly significant, $t(12) = 6.50$, $p < 0.00005$. For the individual comparisons testing pairs differing in the sizes of the visual dimensions (indicated by the horizontal arrows in Figure 9), one can see fragmentation increases for lower numbered stimuli and decreases for higher numbered stimuli, whether convergent or divergent. Again increasing the size of the binocular overlap region decreased the fragmentation. One of the four individual visual dimension factor comparisons only marginally failed to reach significance. These results are summarized in the fifth and sixth rows of Table 3.

Again, in both the pairs comparing display modes (indicated by the vertical arrows in Figure 9), the divergent member was more fragmentary than the convergent member by a highly significant amount.

Figure 10. *Stimulus pairs tested are connected by arrows with the more fragmentary stimulus at the base of the arrows. Mean percentage of the number of trials the stimulus at the base of the arrows was judged to be more fragmentary is shown on one side of the connecting arrows with the results of the one-sample t-test and the one-sample Kolmogorov-Smirnov test in parentheses on the other side of the connecting arrows. The significance level of the t-test is shown as indicated by the arrow symbols.*

Experiment 5: Binocular overlap region held constant

For the six stimuli of Experiment 5, the size of the binocular overlap region (factor D) was held constant to the baseline level. For the lower numbered stimuli, C1 and D1, the sizes of the monocular regions (A), the monocular fields (B) and the FOV (C) were increased from the baseline as indicated in Figure 5 and Table 2. Conversely, these size changes were reversed for the higher numbered stimuli, C3 and D3. The results for Experiment 5 are shown in Figure 10.

The overall mean percentage of fragmentation judgments was 52.6 percent (SD = 19.1) with lower numbered stimuli being judged as more fragmentary than higher numbered stimuli. Here the overall effect of changing the visual dimension factor was not significant, $t(12) = 0.50$. Nor were any of the individual paired comparisons significant. For the stimulus pairs differing in the sizes of the visual dimensions (indicated by the horizontal arrows in Figure 10), one can see that there was no effect of the visual dimension factors for any of these stimulus pairs.

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When the size of the binocular overlap region was held constant, the other factors had no effect on fragmentation. These results are summarized in the last two rows of Table 3.

Again, in both the pairs comparing display modes (indicated by the vertical arrows in Figure 10), the divergent member was significantly more fragmentary than the convergent member.

Optical convergence not a factor

We informally tested the effect of optical convergence. A subset of the subjects, the first five, ran the experimental session twice: once with optical convergence as reported here, where the convergence and the accommodation were set to two meters; and once without optical convergence (i.e., with the two optical axes parallel), where the convergence was at infinity and the accommodation remained at two meters. The only difference between sessions was the comparative difficulty subjects had in maintaining fusion in the no optical convergence (parallel optical axes) session, where each of them had to be verbally coaxed back to fusion a number of times.

For the visual dimension factor, the overall mean fragmentation judgement percentages, that lower numbered stimuli were judged as more fragmentary than higher numbered stimuli, are given below.

The results for Experiment 2, with monocular regions held constant, are:

Convergence: 75.6 percent (SD = 21.0), $t(4) = 2.73$, marginally failed to reach significance at the $p = 0.05$ level. Parallel, 75.0 percent (SD = 18.6), $t(4) = 3.00$, $p < 0.05$.

The results for Experiment 3, with monocular fields held constant, are:

Convergence, 84.4 percent (SD = 13.6), $t(4) = 5.64$, $p < 0.005$. Parallel, 80.6 percent (SD = 8.1), $t(4) = 8.47$, $p < 0.005$.

The results for Experiment 4, with FOV held constant, are:
Convergence, 78.1 percent (SD = 12.5), $t(4) = 5.03$, $p < 0.01$. Parallel, 75.6 percent (SD = 14.2), $t(4) = 4.03$, $p < 0.05$.

The results for Experiment 5, with binocular overlap region held constant, are:

Convergence, 59.4 percent (SD = 23.0), $t(4) = 0.91$, not significant. Parallel, 55.6 percent (SD = 16.7), $t(4) = 0.75$, not significant.

For the optical convergence session, the results for this subset of subjects reflect completely the results for the total group of subjects although, of course, the statistical power in the informal subset analysis was lower. For this subset of subjects, the visual dimension factor results with and without optical convergence were the same. The same is true for the display mode comparisons: For the five experiments, in both the convergence and the parallel optical axes sessions, all the individual comparisons testing the display mode factor indicated that, again in all cases, the divergent display mode was judged as more fragmentary than the convergent display mode a higher percentage of the time. All these tests were significant at the p < 0.01 level or better. The results with and without optical convergence were indistinguishable, which indicates that this was not a factor in the main results reported here.

Summary of results

Transitivity is preserved in the results in each of the individual experiments and for the total set of experiments (i.e., there are no logical contradictions in the ordering — the direction of the arrows — in Figures 6-10).

With regard to the display mode factor, the greater fragmentation with the divergent mode is replicated in every case where the two display modes are compared in each of the five experiments, as shown by all the vertical arrows in Figures 6-10. This effect is invariant over all the changes in the visual dimension factors and the effect is stronger than the effect for any of these other factors as indicated by the comparatively larger percentages for the vertical lines in Figures 6-10. Over a wide range of conditions, when the only difference is the display mode, the divergent display mode will lead to more fragmentation of the image than the convergent display mode. Using a different method, this confirms previous results on the luning effect (Melzer and Moffitt, 1991; Klymenko et al., in preparation), a weaker form of fragmentation. (For those readers who can free fuse, one can test this by fusing the two images in the middle panel of Figure 4, taking care to fixate on the fusion locks.)

We can see a pattern in the combined visual dimension factor results for Experiments 2-5 shown in Table 3. We can see from the first row in each of Experiments 2, 3 and 4 that each time the size of the binocular overlap region (factor D) decreased, the image was judged as more fragmentary. Conversely, as shown in the second row in each of Experiments 2, 3 and 4, each time the size of the binocular overlap region was increased, fragmentation decreased. In Experiment 5, where the binocular overlap region was held constant and the other three visual dimension factors were either all increased or all decreased, there was no effect on fragmentation. This indicates a strong effect of the binocular overlap factor on fragmentation.

When the effect of the other three visual dimension factors is examined across Experiments 2-5, one can see that none of them had a consistent effect on fragmentation. Although highly unlikely, it is logically possible that the effects of the other factors might have exactly canceled each other out across the increases and decreases in the four experiments.

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Given the differing sizes of the increases and decreases as shown in Table 1, this possibility is nil.

We are thus led to conclude that of the four visual dimension factors — the size of (A) the monocular regions, (B) the monocular fields, (C) the total FOV, and (D) the binocular overlap region — only the size of the binocular overlap region appears to be important. When the binocular overlap region is increased, fragmentation decreases and vice versa.

Unlike previous experiments on luning in which subjects were free to inspect the FOV (Melzer and Moffitt, 1991; Klymenko et al., in preparation), we controlled the fixation of the observer, limiting it to the center of the FOV, thus controlling the retinal regions of the observer that were stimulated by the monocular fields. The decrease in fragmentation caused by the increase in the size of the binocular overlap region may have been due to one of two factors that were confounded here. (1) It may have been due to the larger size of the binocular overlap region per se; or (2) it may have been due to the fact that the binocular overlap borders were more distant from the fixation location. We discuss this in the next section.

In summary, there are three main results on fragmentation of the FOV, with the caveat of central fixation: First, optical convergence is not a factor. Second, divergent FOVs fragment more than convergent FOVs. Third, decreasing the size of the binocular overlap region increases fragmentation, while changes in the sizes of the monocular regions, the monocular fields and the FOV are not factors. In addition, as we discuss in the next section, the location of the blind spot in the nasal retina is not a factor.

Visual neurophysiology and ecological optics

The nasal retina is the portion of the retina on the nasal side of the fovea. The fovea, is the region of highest acuity which receives the projection of the portion of an image that is fixated. The other side of the fovea, away from the nose, is referred to as the temporal retina (see Figures 11 and 12).
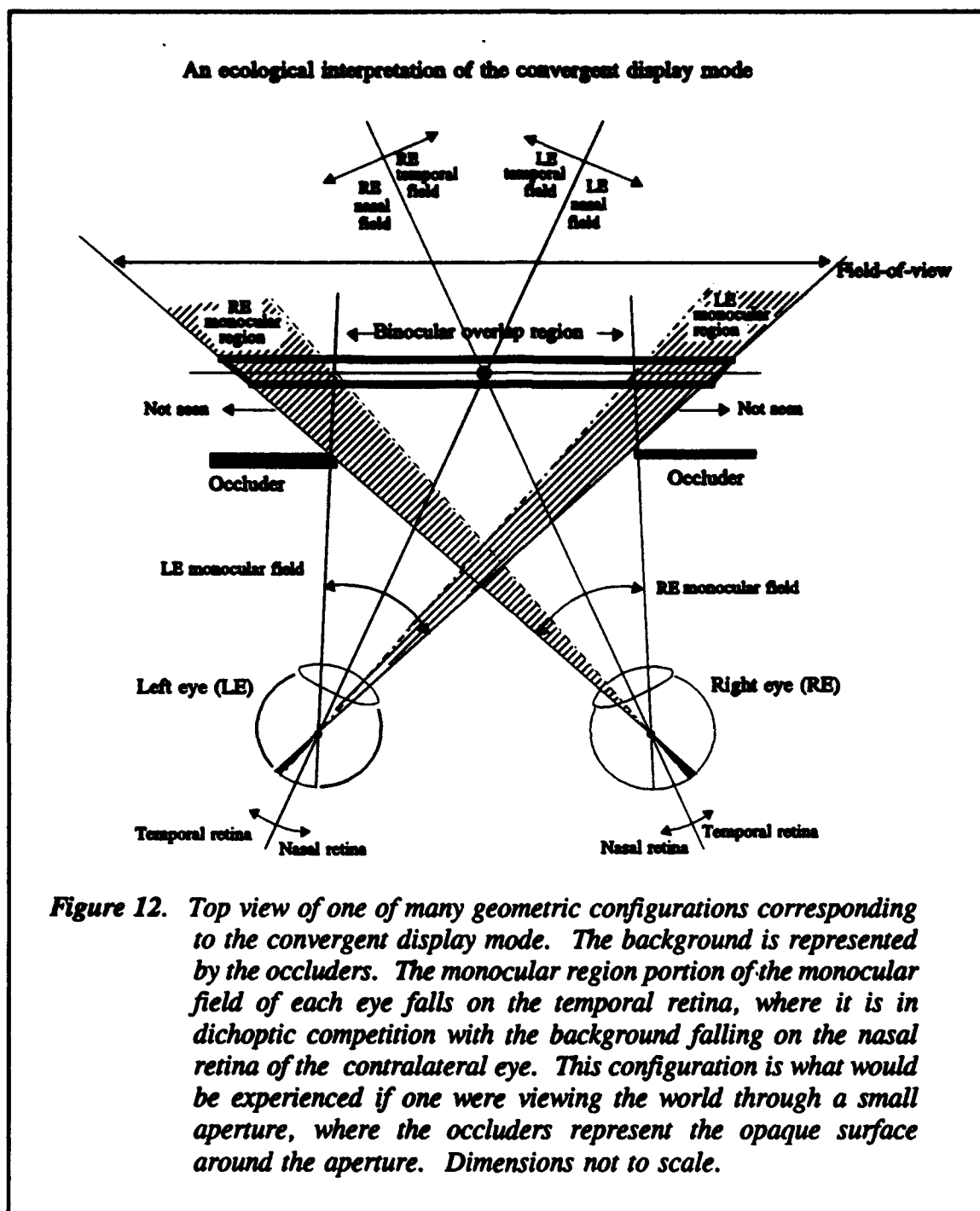
As the retinal image is optically inverted, the temporal retina of each eye receives the projection of the nasal half of the monocular field, and the nasal retina receives the temporal half. The nasal and temporal retinas are distinct in a number of ways, which we will examine in light of our results.

The largest differences in the fragmentation results occurred in the stimulus pairs that tested the display mode factor. The greater fragmentation of the divergent FOV compared to the convergent FOV was replicated for nine stimulus pairs. The only difference between the comparisons that tested display modes was the retinal location receiving the projections of the monocular regions (see Figures 11 and 12). In the divergent mode, each monocular region was the binocular combination of a portion of the monocular field located in the nasal retina of the informational eye with the monocular field border and background located in the temporal retina
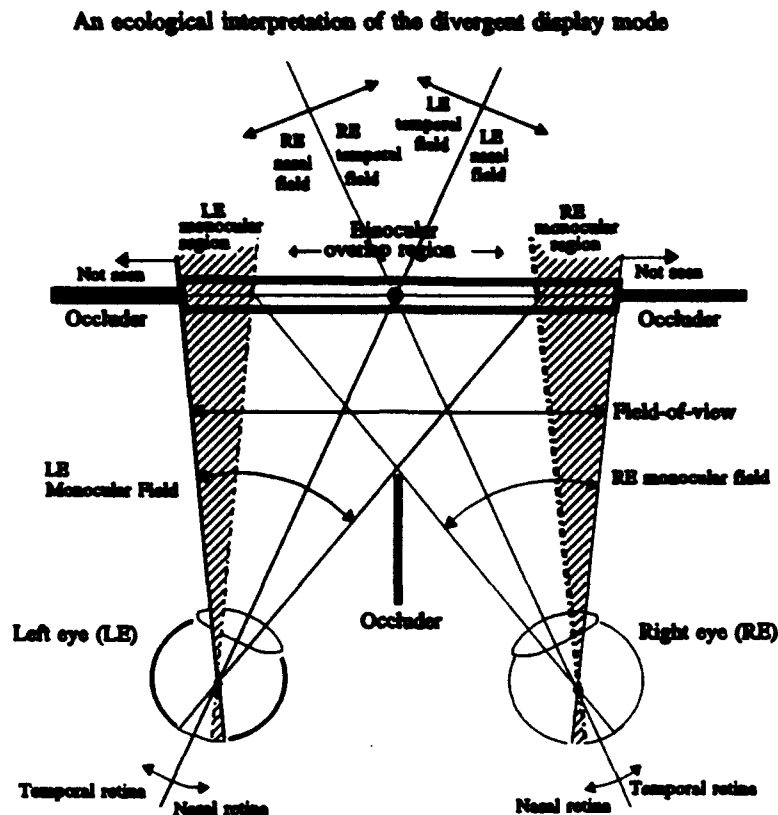
Figure 11. *Top view of one of many possible geometric configurations corresponding to the divergent display mode. The background is represented by the occluders. For each eye, the monocular region portion of the monocular field projects onto the nasal retina, where it is in dichoptic competition with the background, represented by the central occluder in near space, falling on the temporal retina of the contralateral eye. Dimensions not to scale.*

of the contralateral, noninformational, eye. Conversely, in the convergent mode, the monocular region was the binocular combination of a portion of the monocular field located in the temporal retina of the informational eye with the monocular field border and background located in the nasal retina of the contralateral, noninformational, eye. In both cases, the monocular field of each informational eye was in dichoptic competition with the border and background of the contralateral noninformational eye. The display mode results show that the dichoptic competitive strength of the border and background of the noninformational eye was greater when they were located in the temporal retina in the divergent display mode compared to when they were located in the nasal retina in the convergent display mode.

Figure 12. Top view of one of many geometric configurations corresponding to the convergent display mode. The background is represented by the occluders. The monocular region portion of the monocular field of each eye falls on the temporal retina, where it is in dichoptic competition with the background falling on the nasal retina of the contralateral eye. This configuration is what would be experienced if one were viewing the world through a small aperture, where the occluders represent the opaque surface around the aperture. Dimensions not to scale.

As shown by the visual dimension factor results, fragmentation tends to increase as the binocular overlap region becomes smaller. That is, as the border and background move closer to central fixation, their dichoptic competitive strength tends to increase. This happens whether they are located in the temporal retina due to a divergent mode, or the nasal retina due to a convergent mode. While the visual dimension factor results were not as strong as the display

mode results, as indicated by the relatively lower horizontal arrow percentages in Figures 7-9, it does lead us to conclude that the dichoptic competitive strength of the monocular field border (separating the background and monocular field) is stronger when it is closer to central fixation. Below we discuss these results in the light of visual neurophysiology and ecological optics.

First, what leads to increased dichoptic strength when a stimulus is located in the temporal as opposed to the nasal retina? One possibility is the location of the blind spot, a small, approximately circular, blind region of the nasal retina, where the optic nerve exits. This could hypothetically lead to a weakening of the nasal retina in dichoptic competition. The blind spot is centered around 15.5 degrees of visual angle from central fixation in the horizontal direction in the nasal retina and extended from around 13 to 18 degrees. The monocular fields of some of the divergent display mode stimuli extend out to 13.7 degrees (D3 in Experiment 2, D1 in Experiment 3, and D3 in Experiment 5) and therefore overlapped with the blind spot (see Figure 5). This was not the case for any of the convergent display mode stimuli. If the blind spot were an influence, one might expect that the differences between the convergent and divergent display modes would have been different for those paired comparisons where the blind spot overlapped from those comparisons where it did not overlap. This was not the case as can be seen in Figures 7, 8 and 10 showing the results for Experiments 2, 3 and 5, respectively. The differences between the C1 and D1 stimuli were just as great as the differences between the C3 and D3 stimuli. The display mode effect was just as pronounced in the paired comparisons where the blind spot was clearly not involved as it was in the cases where the monocular fields in the divergent display mode overlapped the blind spot. Ramachandran (1992, 1993) has shown that the blind spot is "filled in" by visually interpolating from neighboring regions. He has psychophysically disproved the more intuitive viewpoint that the blind spot is disregarded passively as occurs with the other much larger "blind spot" — the back of the head. One would thus expect the blind spot to fill in its local regions — monocular fields or background. How strong this subjective visual representation in itself becomes in terms of dichoptic competition is a tough question for some clever future research; however, in our results the blind spot was not a factor.

The functional roles of the temporal and nasal retina may provide some ecological insight on our display mode results. Ecological optics, roughly speaking, means analyzing the visual system's functional adaptation to the geometry of the visual world (Gibson, 1979). When one is fixating a point in near space, such as one's hand for example, then points in front of the fixation point — closer to the observer — project onto the temporal portion of each retina, and points immediately beyond the fixation point project onto the nasal portion of each retina as shown in Figure 13. If the points are sufficiently distant from the fixation point, they will produce diplopic images, where each of the two diplopic images of each point will be in dichoptic competition with the more distant background. It appears that the visual system may incorporate a strategy whereby nearer objects projected onto the temporal retinas dichoptically dominate their competing backgrounds more thoroughly than points in far space. This makes sense functionally as objects closer to oneself are likely to be of more immediate concern.

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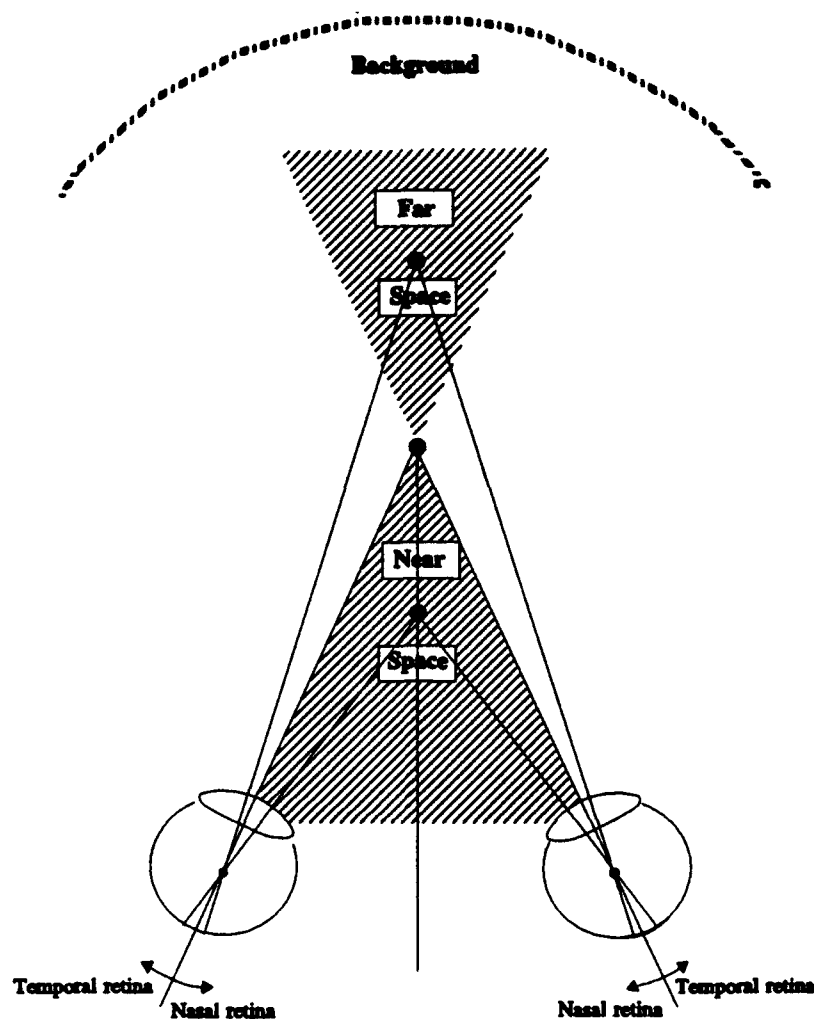
Figure 13. *Retinal projection of non-fixated object points in far space and near space. Symmetrical image points on the nasal retinas representing object points in far space are in dichoptic competition with corresponding points on the contralateral temporal retinas representing the far background. Conversely, symmetrical image points on the temporal retinas representing object points in near space are in dichoptic competition with corresponding points on the contralateral nasal retinas representing the far background.*

Grusser and Landis (1991) have suggested that the temporal retina may be specialized for "near-distance action space" or "grasping space." In support, Grusser and Landis (1991) argue in terms of visual neurophysiology where they note that the object points falling in near space along a line connecting the fixation point and the point between the observer's eyes are uniquely

represented in the visual system. These object points are projected onto symmetrical points of both eyes' temporal retinas (see Figure 13). Further on in the visual system, their field representations in visual cortex are functionally connected via the corpus callosum. The importance of symmetrical points on the two temporal retinas may also be important in evaluating the depth relations of objects in near space via parallax movement (see Regan, 1991). Thus, it makes ecological sense that the images of objects in the all important near space, on the temporal retinas, would dichoptically dominate the images of the far background on the nasal retinas. Presumably, they would dichoptically dominate the background more so than the images of objects in far space on the nasal retinas would dichoptically dominate the background on the temporal retinas, which is exactly what our display mode results show.

Another ecological interpretation of our results concerns the natural FOV the visual system expects and the reduced display FOV it receives in a partial binocular overlap display, and how these expectations were differentially confounded by the convergent and the divergent display modes. The normal unencumbered human FOV is divergent and is around 200 degrees of visual angle, with the binocular overlap region around 120 degrees of visual angle. The cells in the visual system which receive input from the far peripheral nasal retina are neurophysiologically distinct in a number of ways from the cells which receive binocular input (see Guillery and Stelzner, 1970; also see discussion in Zeki, 1993). In the lateral geniculate nucleus (LGN), an early waystation of the visual system, these cells form a region known as the monocular crescent. The monocular crescent processes input from the monocular regions in the normal FOV. When the FOV is artificially reduced, such as in an HMD with a partial binocular overlap mode, the artificial monocular regions project onto retinal areas which normally send input to binocular areas of the LGN and on to the visual cortex. This brings the various processes of binocular vision into play, including for example, dichoptic competition and binocular rivalry, interocular suppression and monocular dominance, and also potentially stereoscopic disparity (e.g., see Gillam and Borsting, 1988; and Kaye, 1978).

Following the ecological line of reasoning, since the visual system has never encountered anything like an HMD in its evolutionary history, it processes the artificial displays in terms of potential real world configurations. Possible configurations for the divergent and the convergent display modes are shown in Figures 11 and 12, respectively. There the dark backgrounds are interpreted as a number of occluders. There are a large number of possible geometric configurations, extensively described by Barrand (1979) in his seminal dissertation on binocular occlusion — a term which means occluded for only one of the two eyes. DaVinci stereopsis, a more recent term, means the same thing. Which of the many possible geometric configurations the visual system interprets will presumably determine the visual processing mechanisms brought into play. For example, Melzer and Moffitt (1991) suggest that the convergent mode induces less luning because it is more ecologically valid, that is, closer to a natural viewing situation. The convergent mode simulates viewing the visual world through an aperture, as shown in Figure 12, where the monocular regions are seen in the same depth plane as the binocular region, and presumably the dark background is seen as the occluding portion of the aperture, which the visual system would tend to suppress. They suggest that the divergent mode is less ecologically valid in that the binocular region is seen as closer in depth than the

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monocular regions (see Figure 2 in Melzer and Moffitt, 1991). They base their conclusions on Shimojo and Nakayama's (1990) and Nakayama and Shimojo's (1990) work showing how the visual system uses the location of monocular regions to settle on an overall interpretation of the FOV.

A number of recent studies have shown the importance of monocular stimuli, including monocular regions, in the overall processing of binocular images (Gillam and Borsting, 1988; Kaye, 1978; Nakayama and Shimojo, 1990; Nakayama, Shimojo and Ramachandran, 1990; Nakayama, Shimojo and Silverman, 1989; Ono, Shimono and Shibuta, 1992; Shimojo and Nakayama, 1990; also see Blakemore, 1969). The gist of this work is that monocular stimuli, whether unpaired image points or whole monocular regions, when located in normally binocular regions, are seen as binocularly occluded with the visual geometric interpretations and concomitant visual mechanisms that this implies. While the possible ecological interpretations are too extensive to review here, we simply note that our data on the relative tendency to fragmentation of the two display modes can be interpreted within this theoretical framework.

However, our display mode data are at first glance unexpected, when one considers recent psychophysical and neurophysiological findings demonstrating the superiority of nasal over temporal retina. Psychophysically, Falhe and Schmid (1988) report superior hyperacuity and spatial resolution in the nasal retina compared to equivalent eccentricities in the temporal retina, and Fahle (1987) reports that, more so than the converse, the nasal retina binocularly inhibits the temporal retina in direct dichoptic competition. These differences are neurophysiologically reflected in the closer packing of photorecepters (Curcio, Sloan, Kalina and Hendrickson, 1990) and ganglion cells (Curcio and Allen, 1990) in nasal than in temporal retina at equivalent eccentricities. This nasal-temporal asymmetry is further reflected higher up in the visual cortex (e.g., Levay, Connolly, Honde and van Essen, 1985). While these psychophysical and neurophysiological asymmetries are relatively small near the fovea, becoming very prominent at 10 to 20 degrees of eccentricity outside the fovea, these data might lead one to assume a general processing superiority for nasal compared to temporal retinal stimulation (see discussion in Grigsby and Tsou, 1993). However, the superiority of visual processing in one area, such as spatial resolution, does not necessarily imply superiority for other areas, such as dichoptic competition.

At this point, we can only speculate based on a functional interpretation of the nasal and temporal retinas. Both objects in near and in far space will be slightly blurred because they are at different depth planes than the fixation point. The fact that the nasal retina has superior spatial resolution may be because it expects relatively more distant stimuli in far space as shown in Figure 13. The temporal retina, with slightly lower spatial resolution, may nevertheless be a relatively stronger dichoptic competitor with the far background. Sensitivity to relatively lower spatial frequencies in the temporal retina — to grosser details of objects in near space — may allow the temporal retina to sum over a larger area in detecting objects and in driving its dichoptic competitive strength. The spatial resolvability of parts of images — the spatial frequency content — is known to affect the perceived depth relations of those parts (e.g., Klymenko and Weisstein, 1986). A suggestion for further research is to test how the spatial

frequency content of images affect the relative dichoptic competitive strength of nasal and temporal retina.

Conclusions

The eyes are free to scan the visual scene in an HMD and will naturally fixate the region of most immediate importance. Particularly when flying and wearing a heavy helmet, a pilot may be more likely than normal to eye scan a region of interest off to the side of the flight path, rather then turn the head to constantly inspect each new item of interest. When the item is foveated in the binocular region near the binocular overlap border, our results indicate that additional items beyond the border in the monocular region may suffer visibility losses due to dichoptic competition, more so in the divergent than in the convergent display mode. Interestingly, in support of our analysis based on temporal and nasal retina, we have found in informal observations of our experimental displays, that when a monocular region is foveated, the fragmentation differences between the convergent and the divergent display modes are considerably attenuated. Elsewhere, however, we have shown with much larger FOVs than those tested here, that even foveated items have a higher contrast threshold when presented in monocular regions of divergent displays compared to convergent displays (Klymenko, Verona, Beasley, and Martin, 1993). Thus, reducing luning and fragmentation is an important concern in HMDs. Two common sense solutions have been suggested (Moffitt, 1989; Melzer and Moffitt, 1991). They involve altering the relative dichoptic competitive strengths of stimuli in the informational and in the noninformational eyes. First, since it is known that edges, particularly sharp edges, are stronger dichoptic competitors than clear fields and that edges tend to carry adjacent areas into the binocular percept (Kaufman, 1963), it is logical to place a competing edge in the monocular field of the informational eye in order to strengthen it relative to the monocular field border of the noninformational eye. As the edge will bring in adjacent areas of the informational eye, the FOV will look more unitary and there will be less luning. Elsewhere, we have confirmed this (Klymenko, Verona, Martin, Beasley, and McLean, in preparation). How this affects visibility of small adjacent targets remains to be seen. Second, softening (i.e., blurring) the monocular field border of the noninformational eye should in turn weaken its dichoptic competitive strength. Moffitt (1989) reports that this is indeed the case and that this has no noticeable detrimental effect on target detection. However, this should be confirmed in a more precise study.

One obvious question remains. We found that with central fixation the FOVs with smaller binocular overlap regions have more of a tendency to fragment. The distance between the fixation point and the binocular border is confounded here. One might make additional tests to unconfound fixation distance from the border and the size of the binocular overlap region. Our informal observations, however, suggest that the distance between the fixation point and the binocular border is the important factor here.

A few additional facts should be kept in mind. First, a large number of factors are known to affect binocular rivalry and suppression ranging from the sensory to the cognitive

(e.g., Hollins, 1980; Kaufman, 1964; Yu and Blake, 1992; O'Shea and Blake, 1986; see Fox, 1991, and Uttal, 1981 for reviews). Second, there are other effects which may also contribute to luning and fragmentation, particularly where displays contain large dark homogeneous backgrounds. Examples are the Troxler effect, which refers to the perceptual fading in peripheral retinal regions due to adaptation, and Ganzfeld-like effects, which refers to the perceptual fade-out which can occur when viewing a large homogeneous field in one or both eyes (e.g., see Bolanowski and Doty, 1987; and Gur, 1991). How these other effects are related to binocular rivalry is unknown. One should be aware of these additional facts when drawing conclusions on perceptual phenomena in HMDs.

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Appendix A.

Eye exam data sheet

Psychophysical Assessment of Visual Parameters in Electro-optical
Display Systems

VISUAL EXAM

Subject #_____   Age:_____   Date:_____

Old RX: R.E._____   L.E._____
    for distant vision   (Yes) (No)
    for near vision   (Yes) (No)
    Bifocal   (Yes) (No)

AFVT - with glasses if required for distance #3, #2, #1

VA   R.E. line_____20/____   Lateral Phoria #____   ____
FAR L.E. line_____20/____   Vertical Phoria #____   ____
                                  LP = XO >11; VP = Rt Hyper >5, .5 steps

Stereopsis thru line#_____
Lateral Phoria @ Near #_____   ____   LP = XO >13

AUTO REFRACTION (ARK 2000)   P.D. _____

        O.D. _____
        O.S. _____

SUBJECTIVE REFRACTION: (Green > Red)   X-CYL at far
        O.D. _____ 20/   O.D._____ SPH
        O.S. _____ 20/

Lateral Phoria @ Far _____   Vertical Phoria_____

Lateral Phoria @ Far with -1.00 D _____

Lateral Phoria @ 50 cm _____   X-CYL @ 50 cm O.D._____SPH
      Lateral Phoria @ 50 cm +1.00 D _____
      Lateral Phoria @ 50 cm -1.00 D _____
          Calculated ACA ratios   far minus _____
                           near plus _____
                           near minus_____

Appendix B

Manufacturers' list

Hewlett-Packard Company
3404 East Harmony Road
Fort Collins, Co 80525, USA

Edmund Scientific Co.
Edscorp Building
Barrington, NJ 08807, USA

Initial distribution

Commander, U.S. Army Natick Research,
    Development and Engineering Center
ATTN: SATNC-MIL (Documents
    Librarian)
Natick, MA 01760-5040

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